

## Introduction

With the International Space Station Program transition from assembly to utilization, focus has been placed on the optimization of essential resources. This includes resources both resupplied from the ground and also resources produced by the ISS. In an effort to improve the use of two of these, the ISS Engineering teams, led by the ISS Program Systems Engineering and Integration Office, undertook an effort to modify the techniques use to perform several key on-orbit events. The primary purposes of this endeavor was to make the ISS more efficient in the use of the Russian-supplied fuel for the propulsive attitude control system and also to minimize the impacts to available ISS power due to the positioning of the ISS solar arrays.

Because the ISS solar arrays are sensitive to several factors that are present when propulsive attitude control is used, they must be operated in a manner to protect them from damage. This results in periods of time where the arrays must be positioned, rather than autonomously tracking the sun, resulting in negative impacts to power generated by the solar arrays and consumed by both the ISS core systems and payload customers. A reduction in the number and extent of the events each year that require the ISS to use propulsive attitude control simultaneously accomplishes both these goals.

Each instance where the ISS solar arrays normal sun tracking mode must be interrupted represent a need for some level of powerdown of equipment. As the magnitude of payload power requirements increases, and the efficiency of the ISS solar arrays decreases, these powerdowns caused by array positioning, will likely become more significant and could begin to negatively impact the payload operations. Through efforts such as this, the total number of events each year that require positioning of the arrays to unfavorable positions for power generation, in order to protect them against other constraints, are reduced.

Optimization of propulsive events and transitioning some of them to non-propulsive CMG control significantly reduces propellant usage on the ISS leading to the reduction of the propellant delivery requirement. This results in move available upmass that can be used for delivering critical dry cargo, additional water, air, crew supplies and science experiments.



During the past several years, the ISS Program has successfully implemented the use of non-propulsive methods to maintain ISS attitude control for different dynamic operations. Historically, for any dynamic event, ISS control was transferred over to the Russian Segment to maintain a stable attitude using Russian thrusters. The first event to be transitioned from Russian Segment thruster control to Control Motion Gyroscope (CMG) control was the undocking of the Russian Progress vehicle docked to Service Module aft docking port in November of 2008. Since then, the engineering teams have performed analysis and developed new procedures that have allowed the ISS Program to transition RV undockings, Progress propellant purges, Russian EVA depresses and several other operations to United States Orbital Segment (USOS) CMG control. This transition has not only saved a significant amount of valuable ISS resources, but also simplified operations, reduced operational risk, significantly simplified, and in many cases eliminated, complex analysis required for each event and reduced ISS contamination.

During quiescent operations, the ISS uses CMG Momentum Management (MM) controller to maintain a Torque Equilibrium Attitude (TEA). This is a non-propulsive method of control that allows full autotrack articulation of USOS Solar Arrays, thus maximizing power generation for payloads use and system operations. However, there are multiple events (maneuvers for docking/undocking, attitude holds for propellant purges, vents, solar array efficiency tests, etc.) that require thruster control. Due to the potential forces exerted by the attitude control jets, as well as potential impingement of unburnt propellant, propulsive events can cause load exceedances on USOS appendages unless the appendages are positioned to mitigate the risk. This positioning of the solar arrays negatively impacts the power generation capability of the ISS during the event and can require significant powerdowns of equipment to maintain battery levels. Additionally, positioning the arrays by parking the Beta Gimbal Assemblies (BGAs) introduces a USOS Solar Array thermal structural loads concern caused by the so called longeron shadowing phenomena.

Each wing of the USOS Solar Arrays have four longerons that extend from the canister with tipshell covering the end (see figure 1).

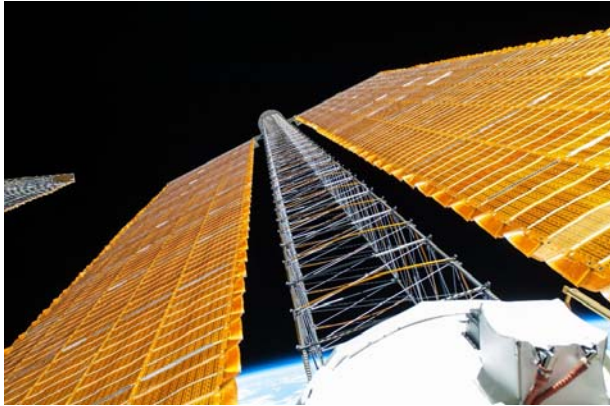


Figure 1 USOS Solar Array Mast

Longerons are thermally isolated from each other and if longeron #1 (Figure 2) is shadowed, it becomes cooler than the other three, so it constricts. Due to all four longerons being attached to the same relatively rigid plane, a loading condition is established and longeron #1 pulls the tipshell toward the canister causing longerons #2 & #4 to go into compression and longeron #3 in tension. The compression load can lead to a buckling failure of the longeron. Contrary, if the shadow is on longerons #2, 3 & 4, it causes those longerons to be cooler than longeron #1 establishing similar conditions as in previous case, where longeron #1 pushes the tipshell away from the canister, causing longeron #3 to go into compression and 2 & 4 in tension, which may lead to the compression load buckling failure.

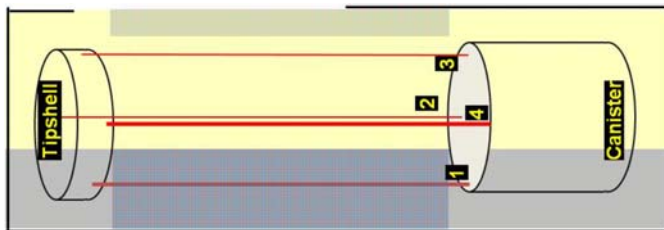
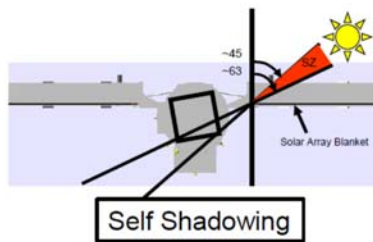


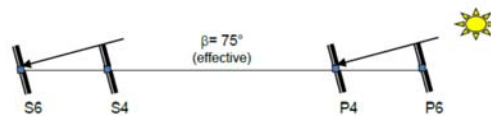
Figure 2 USOS Solar Array longeron schematics

If the array has to be positioned for thruster plume loads or array erosion concerns in case of a dynamic event, extensive longeron shadowing analysis has to be performed. Combination of thermal and plume loads creates significant concerns for structural integrity of USOS Solar Arrays.

There are two types of longeron shadowing: self and adjacent. A self-shadow is cast on a mast by its own blankets so the shadow source is relatively close to the longerons. An adjacent shadow is cast on a mast from its adjacent pair, where the shadow source is 50 feet from longeron. See Figures 3 and 4



Self Shadowing



Adjacent Array Shadowing

Figure 3 Solar Array longeron self shadowing  
Figure 4 Solar Array longeron shadowing with adjacent array

### Russian Vehicle Undocking

The negative impacts to power generation, as well as the potential for longeron shadowing loads are why it is so important to reduce the amount of propulsive dynamic events and transition as many as possible to non-propulsive CMG control. During early stages of the Program, to undock any Visiting Vehicle from ISS, the United States Orbital Segment would hand control over to the Russian Segment, which would propulsively maneuver the ISS to undock attitude, perform attitude control during event, clean up rates imparted into the ISS during the operation post event and maneuver ISS back to torque equilibrium attitude. This led to changes in appendage positions, the development of complex timelines, multiple analyses and extensive coordination between US and Russian teams.

Once all appendages were positioned, and RS was in control, ISS was maneuvered to undock attitude. See figure 5. Since propulsive attitude control is not allowed while docking mechanism hooks are driving, ISS was commanded to go "free drift" for the period of four to five minutes while docking mechanism operates.

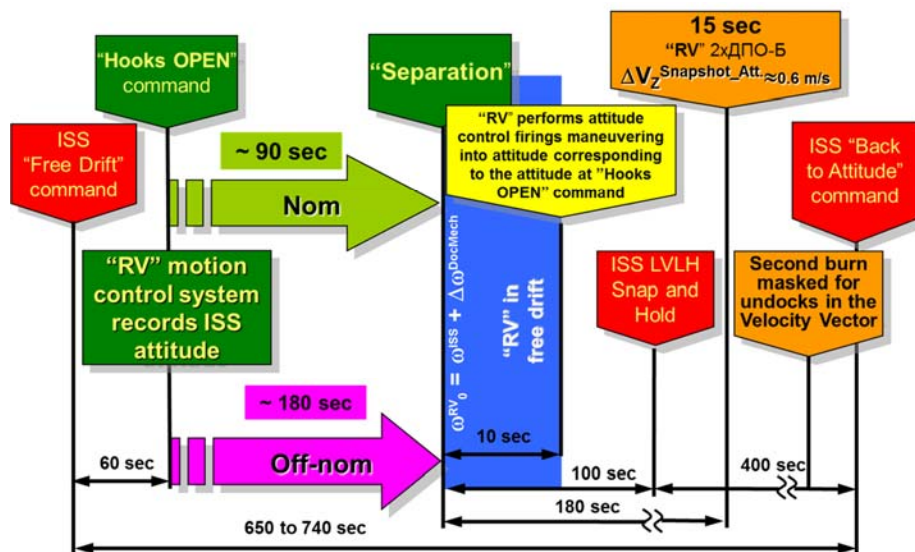


Figure 5 Russian vehicle undock timeline

Post separation, Russian Vehicle remained dormant gaining positive clearance from  $\sim 0.1 - 0.12 \text{ m/s}$   $dV$  imparted into the vehicle by docking mechanism spring pushers. Docking mechanism nominal operational dispersions could lead unfavorable vehicle rates with minimal longitudinal velocity if  $0.09 \text{ m/s}$ , maximum transverse velocity if  $0.03 \text{ m/s}$ , maximum yaw/pitch rotation  $0.5 \text{ deg/s}$  and maximum roll rotation  $0.2 \text{ deg/s}$ . Ten seconds post physical separation, Russian Vehicle automatically regained attitude control maneuvering departing vehicle to the attitude relative to the ISS that it acquired prior to "hook open" command. One hundred seconds post Visiting Vehicle separation, ISS regains attitude control and "snaps" current attitude it drifted to. Eighty seconds later, Russian Vehicle initiated a 15 second "backaway" burn increasing departing vehicle separation rate to  $\sim 0.6 \text{ m/s}$ . After five hundred seconds post RV separation ISS was maneuvered back to nominal Torque Equilibrium attitude. See Figure 6. Seventy minutes after the event control was transferred back to the USOS and 110 minutes post undock ISS went back to nominal operations.

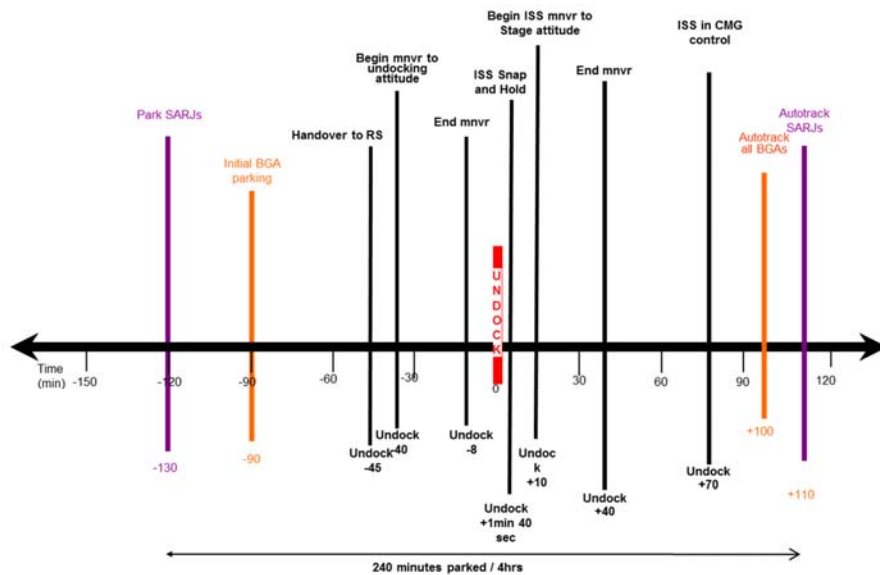


Figure 6 Russian Vehicle undock timeline

Obviously, 240 minutes of parked arrays caused ISS to perform significant powerdowns, impacting science and system operations.

The first event that we transitioned from ISS propulsive control to non-propulsive was the undocking of Progress vehicles docked to SM aft. New approach allowed to fully autotrack arrays and maintain USOS attitude control during the entire time of operation making it absolutely seamless to other USOS systems.

The next step was to allow nadir and zenith vehicles to undock in the same manner: allow ISS to maintain non-propulsive control while flying the nominal TEA. This task was of a greater complexity since certain safety constraints required ISS to be maneuver to high pitch attitude to avoid collision with uncontrolled vehicle on the following orbits. See Figure 7. In order to meet all safety constraints and allow ISS to remain in TEA, RSC-Energia specialists developed a new crew procedure that allows Soyuz crew to take control over in case of the failure and manually safely fly vehicle away from the ISS.

Several operations had to be changed on the departing vehicle as well as the ISS side

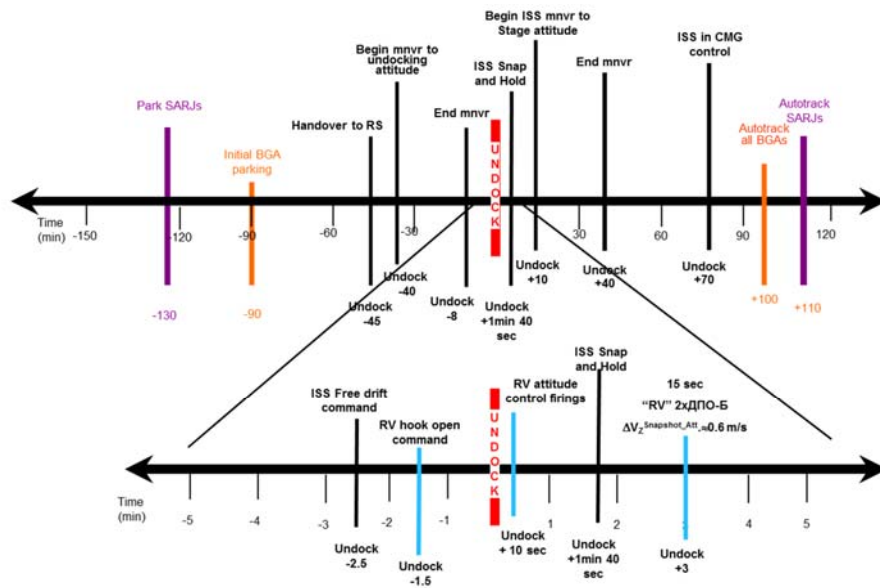


Figure 7 Integrated ISS and departing RV timeline

Since the Russian vehicle is undocking into nadir/zenith direction, in order to ensure safe separation, vehicle has to perform two separation burns: one to move the vehicle away from the ISS and the second burn to ensure safe separation on the following orbits. In general the Russian Vehicle departure timeline remains the same, where vehicle regains attitude control 10 seconds post separation and initiates a backaway burn 170 seconds later. However, the burn is performed using two pairs of thrusters instead of one to increase reliability, thus decreasing burn time to 8 seconds in order to achieve the same thrust magnitude as previously executed. Once the 8 second burn is complete departing vehicle performs a roll maneuver to prepare vehicle for the second burn. At 260 seconds post separation, a 30 second burn is performed using 2 pairs of mid-ring thrusters (ДПО-Б) with thrusters pointing at 45 degrees in -Y and +Z direction providing posigrade burn for a vehicle. See figure 9.

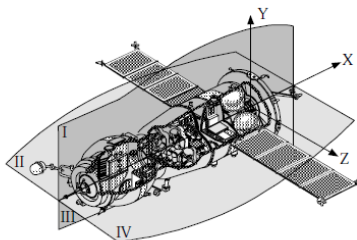


Figure 8 Soyuz Vehicle coordinate system.

Performing vehicle undock in TEA under CMG control allowed us to significantly simplify ISS operational timeline as shown in Figure 10.

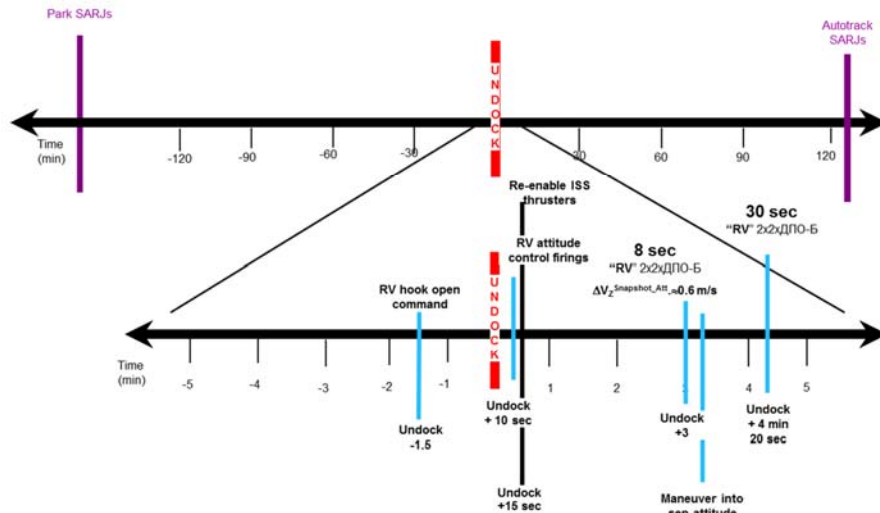


Figure 9 Improved ISS and RV integrated timeline

For the Russian Vehicle departure analysis RSC-E generated a simulated Soyuz thruster firing histories database that included a total of two sets of 6912 simulations of Soyuz separations from ISS nadir and zenith ports in TEA. Simulations contained relative motion of the ISS and departing Russian Vehicle from the docking point to the completion of second burn (350 seconds). Sims included 1728 no thruster failure cases of which 768 nominal, most expected cases; 576 one sigma deviations, which may be expected in 10-20% cases and 384 two – three sigma deviation cases, which are theoretically possible but never experienced in real flight. Database also included 5184 simulated thruster failure cases: single thruster failure; single manifold failure (two thrusters on the same manifold) and two co-located thruster failures (on separate manifolds). Teams also performed probabilistic risk assessment to determine the risk of such thruster failure, as shown on Figure 10.



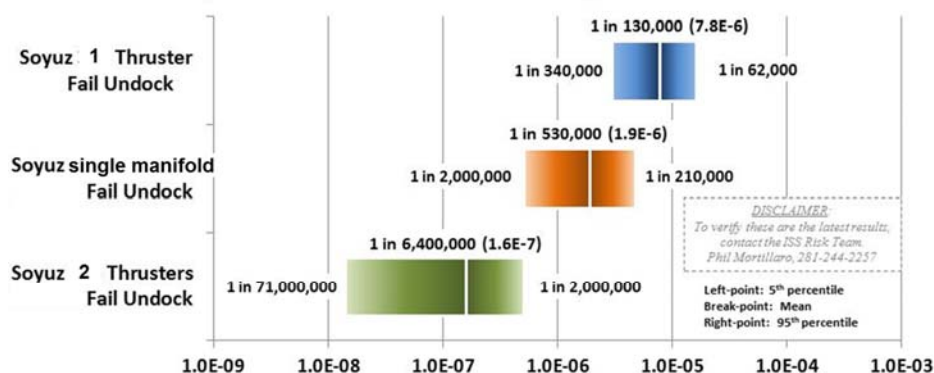


Figure 10 Probability of Soyuz thruster failures during undock

As the first step in certification of this operation, NASA teams performed analysis to determine controllability options for the ISS and from the start determined that due to departing vehicle plume loads paired with separation spring push, USOS Solar Arrays could not be fully autotracked. The next step was to determine optimal SARJ positions that would provide minimal loads and torques but at the same time permit autotrack of BGAs. In this case even though full autotrack is not possible, BGA autotrack allows to minimize/eliminate equipment powerdowns. For different docking ports different SARJ angles were determined to be optimal. Once optimal SARJ position that allows support of contingency Russian thruster control was determined using Russian provided thruster firing histories, NASA Loads Team performed analysis to determine worst case cumulative momentum in Yaw, Pitch and Roll and provided that data to NASA Guidance Navigation and Control team. Several different control methods were analyzed. However, since the disturbances from vehicles undocking from zenith and nadir ports were high, the decision was made not to use CMG Momentum Management controller as in SM Aft case undock, but use CMG Attitude Hold controller instead. CMG MM controller is not designed to fight external disturbances, but to look for an optimal torque equilibrium in a slowly changing environment. On the other hand CMG AH controller was designed specifically for holding attitudes during disturbances distributing thruster firings between attitude control and CMG desaturation requests. First CMG controlled undock from a nadir port in TEA was performed from ISS MRM1 nadir port during 39S departure. It was performed using CMG MM controller and showed up to 86% CMG saturation rate. This made teams a little uncomfortable and later the decision was made to unify operations by transitioning all nadir and zenith undock to more stable CMG AH controller.

ISS GNC Engineering team analysis has shown that 0 to 10 thruster firings may be requested by GNC system during this operation. Several undockings were performed since November of 2014 using between 0.5 and 0.8 kgs of propellant vs 30 to 40 kgs used for these events previously.

In parallel clearance analysis was performed using RSC-Energia developed database that along with thruster firing histories provided information on Russian Vehicle relative location to the ISS. Analysis included nominal and failure cases. All cases showed sufficient clearance margin for Solar Array specific position as well as full sweep for both nadir and zenith ports as shown on figures 11 and 12 for ISS zenith port and figures 13 and 14 for ISS nadir port.

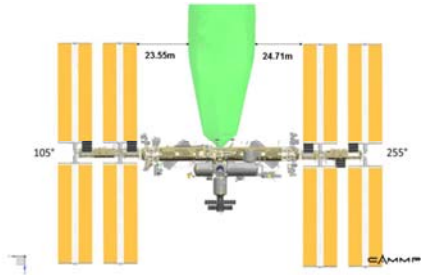


Figure 11 Nominal departure corridor

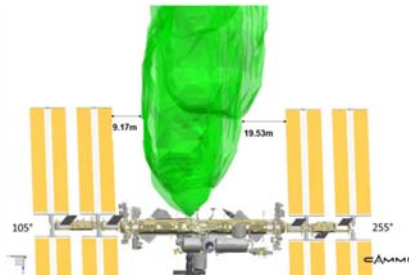


Figure 12 Worst case contingency departure corridor

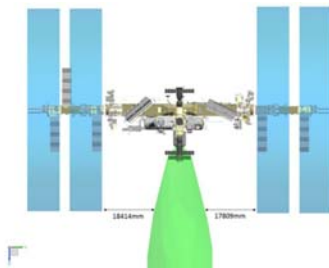


Figure 13 Nominal departure corridor

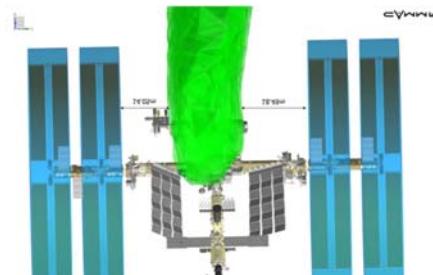


Figure 14 Worst case contingency departure corridor

The newly adopted timeline requires SARJ mechanisms to be parked on target (at the time when Solar Array passes through the target angle) to minimize vehicle disturbances three to four hours prior to the event. Prior to vehicle undock ISS remains in nominal flight TEA using CMG MM controller. One orbit prior to the event ISS docking mechanism hooks open and approximately at the same time ISS ADCO team prepares ISS for post undock configuration. Approximately 20 minutes prior to undocking based on system health status ISS Flight Director gives a final go/no-go for undocking. Undock command is sent by MCC – Moscow to open departing vehicle hooks and it takes approximately 90 seconds to drive the mechanism. Fifteen seconds after undocking based on undock confirmation flag from the Russian docking mechanism, ISS automatically transitions to CMG AH controller with desats allowed at 95% saturation rate. At the same time CMGs adjust ISS attitude to post undock TEA. In about half orbit ISS is moded back to nominal CMG MM controller. And one orbit later SARJs return to autotrack.

These efforts on top of simplifying joint operations, developing new operational techniques, reducing loads and contamination, saving ~200 kg of ISS propellant annually also reduced negative effect of attitude excursions on external payloads, that often require specific attitudes to perform valuable scientific experiments.

### Propellant Purges

Prior to undocking Russian Progress vehicles, the lines that connect them to the ISS fuel and oxidizer supply tanks must be purged. In the past, this required the ISS to mode to propulsive attitude control on Russian thrusters. Starting in 2013, the US GNC Engineering teams undertook an effort to analyze the torque resulting from these purges in an effort to determine if these could be performed under US CMG control.

Initial investigation focused on the purges for the Progress vehicles docked to the DC-1 port. The approximate expected exit velocity of the purge material had been established by photogrametric means earlier in the Program. The Engineering teams modeled the expected torques by using this approximate velocity, the expected mass of the purge materials, as calculated from the known volume of the fuel and oxidizer lines, as well as the direction of the vent nozzles. Using these calculations, the team was able to model a torque time history for both the fuel and oxidizer purges and perform the associated CMG controllability assessments. Due to the geometry of the purge nozzle relative to the center of gravity of the ISS, the resulting expected torque from the purge events was predicted to be relatively minor; and, it was determined that US CMG control was a viable control option for the purge of the Progress on DC-1.

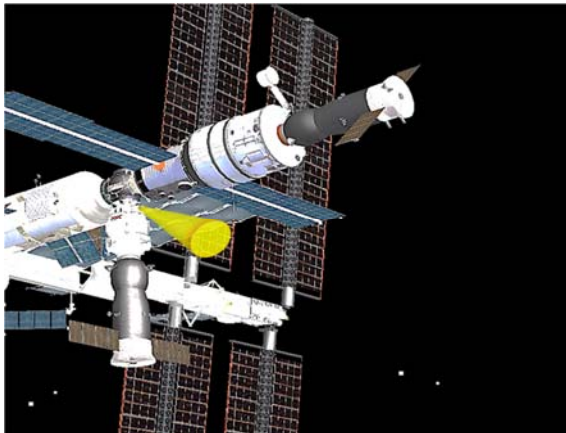


Figure 15 – Direction of purge materials, DC1 Progress

The first instance of this event performed on-orbit using this new approach was the 54P Progress purge, in early 2014. The event was successful, with no GMC desaturation firings required. Numerous subsequent purges of the Progress on DC-1 have been performed successfully using CMG control, establishing this technique as the new baseline mode for the purge of the Progress on DC-1.

After establishing the technical viability of performing Progress prop purges on CMG control for the DC-1 port, the team began assessment of the purge for a Progress docked to the Service Module aft port. The calculation methodology for torque prediction was the same as was used for the DC-1 port. However, due to the location and pointing direction of the aft port purge nozzles, the resultant expected torques were much higher.

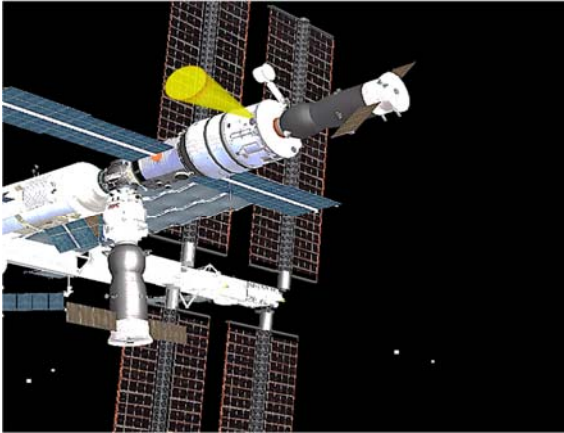


Figure 16 Direction of purge materials, SM Aft Progress

Based on their assessments, the Engineering teams predicted that CMG control was a viable option, but that some CMG desaturation firings could be expected. The teams estimated that these firings would number somewhere in the range of 5-18 in total for the whole event, dependent upon the particular circumstances surrounding the actual event. The Progress 58P purge was attempted on CMG control in August, 2015. The event was a success, with 10 CMG desaturation firings required. This resulted in a prop usage of approximately 1.6 kg.

Each of these events, when performed on Russian segment propulsive attitude control, required approximately 10 kg of prop per event. Performed under CMG control, with CMG desaturation firings as needed, the prop cost for the DC-1 purge and SM aft purge are expected to be approximately 0 kg and 1-2 kg respectively. Based on the anticipated Flight Program, transitioning these two events from Russian segment thruster control to CMG control is expected to result in an annual ISS prop savings of approximately 35-40 kg per year.

#### **Russian EVA depress**

Historically, events with significant disturbances, such as the airlock depressurizations associated with extra-vehicular activity (EVA), have been performed using the RSOS attitude control system to provide stable attitude control. However, transfer of attitude control between US and Russian segment is labor intensive and Russian propulsive attitude control uses significant amounts of propellant. These predictions of the disturbance torque to the ISS for depressurization of the Russian Segment Pirs airlock were performed employing NASA's DSMC Analysis Code (DAC) to assess the feasibility of using USOS control during these events. The ISS Pirs airlock is vented using a device known as a "T-vent" as shown in Figure 18. By orienting two equal streams of gas in opposite directions, this device is intended to have no propulsive effect. However, disturbance force and torque to the ISS do occur due to plume impingement. The disturbance torque resulting from the Pirs depressurization during EVAs is estimated by using a loosely coupled CFD/DSMC technique. CFD is used to simulate the flow field in the nozzle and the near field plume. DSMC is used to simulate the remaining flow field using the CFD results to create an inflow boundary to the DSMC simulation. Due to the highly continuum nature of flow field near the T-

vent, two loosely coupled DSMC domains are employed. An 88.2 cubic meter inner domain contains the Pirs airlock and the T-vent. Inner domain results are used to create an inflow boundary for an outer domain containing the remaining portions of the ISS. Several orientations of the ISS solar arrays and radiators have been investigated to find cases that result in minimal disturbance torque.

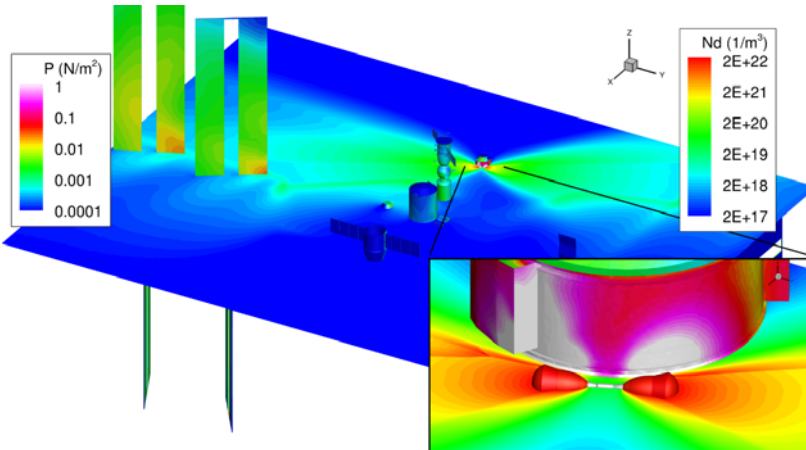


Figure 17 Pirs depress pressure distribution

ISS GNC Engineering community performed controllability analysis using worst case pressure distributions from Pirs T-vent during depress. Analysis results have shown that MM-CMGAH-MM control scheme for DC1 Airlock Depress demonstrated robust controllability, where ISS attitude and attitude rate were sufficiently controlled throughout the Depress. Analysis has also shown that ~ 6 back-to-back desats of 10,000 ft-lb-s magnitude may be expected during depress. Number of expected thruster firings may be as high as 14 per for this event and high momentum is expected at the time of handover back to CMG MM control.

The depress for Russian EVA 41 was performed on August 10, 2015. The system behaved as expected with total of 8 desaturation thruster firings: five during depress event and three at the time of transition from CMG AH to CMG MM. This resulted in a prop usage of approximately 3.0 kg vs the legacy technique (Russian thruster propulsive control) requiring 20-25 kg of prop.

#### Optimal Propulsive Maneuver (OPM)

Beginning in 2012, the ISS Program implemented a new technique by which to perform the maneuvers between +XVV and -XVV. Until this point, when the ISS needed to transition between these attitudes, the Russian Segment Attitude Control System was used to perform the maneuver propulsively. The control system executed the maneuver in a standard Eigen Axis technique with standard control parameters in place with respect to attitude rate and error deadbands. This allowed for a relatively quick maneuver to the destination attitude; but, it came at a significant cost in propellant usage. Due to a desire to reduce propellant usage, the US Guidance, Navigation and Control Engineering teams began to explore maneuver techniques designed to make use of the forces and resulting torques to which the

ISS was naturally exposed. A new method of performing the 180 degree yaw maneuvers, the Optimal Propulsive Maneuver (OPM), was developed. This method uses the United States Thrusters Only (USTO) control method to initiate a maneuver from +XVV (-XVV) in a trajectory that, once the resulting aero torques act on the ISS, will result in a profile to bring the ISS to the -XVV (+XVV). Once the ISS approaches the target attitude, a small number of USTO firings occur to null the body rates and stop the maneuver.

This technique requires only a very modest prop expenditure (approximately 10 kg per maneuver), when compared to the large prop expenditure required for the traditional method (ranging from approximately 50-160 kg per maneuver, depending on the method of ISS roll control). Since inception, the use of this OPM technique has resulted in significant total prop savings. To support Russian visiting vehicle proximity operations requirements, the ISS is maneuvered to -XVV approximately 5-7 times each year, resulting in approximately 10-14 instances of the 180 deg yaw maneuver annually. Each of these events, when done via OPM, save either approximately 40 or 150 kg of prop, each direction.

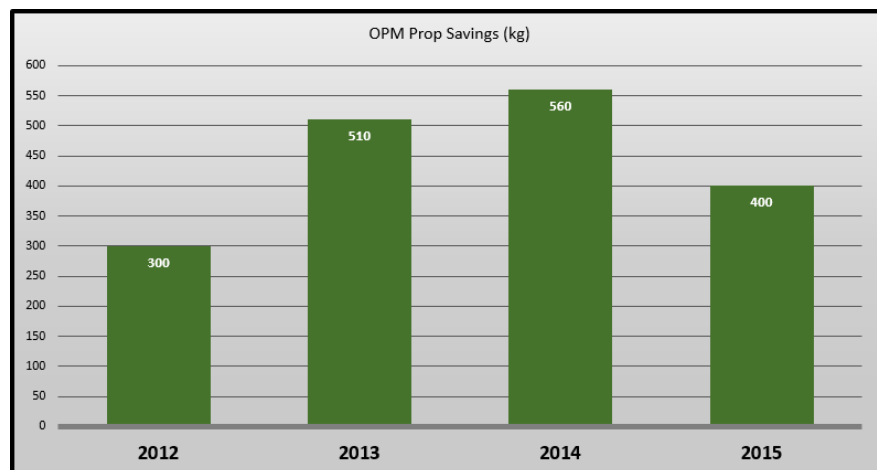


Figure 18 Prop savings per year due to OPM usage

#### Dynamic Events Working Group (DEWG) and DEWG table

Until 2012, planning for and analyzing key ISS dynamic events began at approximately 4-5 weeks prior to the date of the event. In particular, highly complex events such as Russian vehicle dockings were not discussed between the US and Russian technical teams nor defined up until this 4-5 week point. At this timeframe, the Russian teams notified the US teams of the desired parameters (attitude, docking time, window for use of inertial attitude) and the US teams initiated the required analysis. This late event parameter determination regularly contributed to the plans and procedures for these events not being certified and ready until very close to the execution of the event on-orbit. In 2012, the US and Russian teams jointly founded the Dynamic Events Working Group (DEWG) to allow for early determination of key parameters and to facilitate the timely analysis of these parameters and plans for the event. This team now holds a semi-annual face-to-face meeting, supplemented with regular discussions via

The primary product that the DEWG produces is the DEWG Table, a spreadsheet where the key parameters for each upcoming event are documented. These include: ISS attitude, event times, attitude control modes, Thermal Radiator Rotary Joint (TRRJ) angles, Solar Array orientation (Solar Alpha Rotary Joint and Beta Gimbal Assembly angles), Beta angle and ISS visiting vehicle configuration. The DEWG Table is maintained by the ISS Program Systems Engineering and Integration Office on a website that is accessible to all parties throughout the ISS Program, Engineering, Operations and Payloads communities. This serves as the authoritative data source for all parties responsible for assessments and analysis supporting dynamic events. It also is a reference for the payloads community to track, months in advance, the planned attitudes that the station will use in the near future. This information is significant to the external payload operators who are dependent on ISS orientation for data gathering.

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The DEWG also serves as a forum for the proposal and discussion of new ideas and operational techniques associated with dynamic events. Several topics, including updates to Flight Rules, optimization of US Solar Array positioning for the Russian vehicle Kurs long range rendezvous system, selection of optimal attitudes for docking, the use of inertial ISS mode for manual docking, have been discussed and improved via discussions at the face-to-face meetings. The transition of these events from Russian thrusters to CMG control was discussed in this forum.

## Future work

NASA and RSC-Energia teams are actively working on transitioning undocking of the Progress vehicle docked to DC1 nadir port from nominal Russian controlled ZVV to TEA CMG controlled undocking. Since nadir Progress is essential to providing efficient control to the ISS, replacement of the nadir vehicle requires significant amounts of propellant. A new technique is required to provide an ability for the crew to remotely control the vehicle in case of the failure during the departure. Once such technique is developed NASA and RSC-Energia specialists will perform analysis similar to what was done for Soyuz vehicles to approve this operation for implementation. We expect that on top of all other benefits, this transition will save ISS between three and four hundred kgs of propellant annually.

Additionally, other regularly recurring events which are currently being performed on RS thruster control may have the potential to be transitioned to CMG control. One such event is a recurring test of the Service Module solar array efficiency. For these events, the ISS is currently moded to RS thruster control and held at a (0, 0, 0) attitude. It may be possible to perform the event on CMG control. Doing so would save approximately 10 kg of prop for each event.

### Conclusion

Through the expanded use of US CMG control, in substitution for RS thruster control, and the development of the OPM technique, the ISS has realized a significant reduction in the amount of prop required to support normal operations.

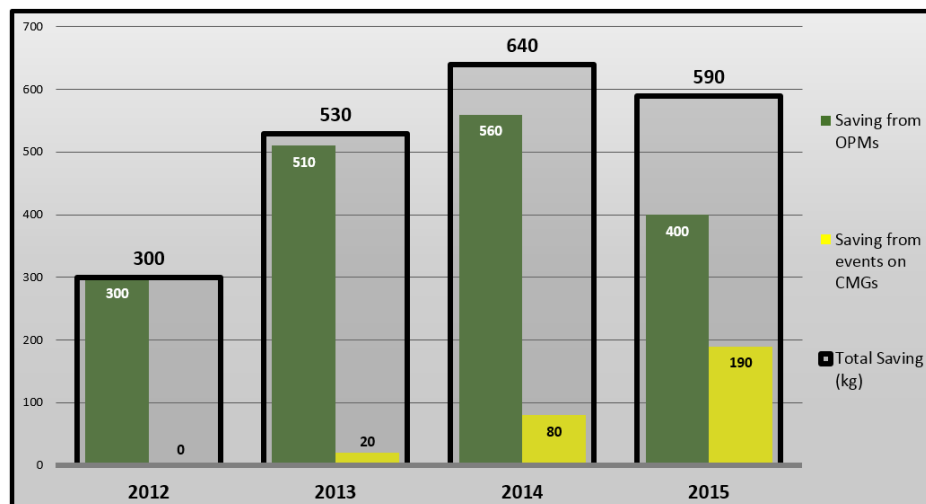


Figure 20 Total Prop savings by year due to OPMs and CMG use

The transition of events to CMG control has helped to alleviate the need to position the solar arrays for several types of recurring events. This has contributed to the ISS having few events per year that require intensive longeron shadowing analysis and cause a powerdown of equipment due to the power deficits that occur when the solar arrays are positioned.